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14. ABSTRACT
The report summarizes progress in understanding plastic strain localization leading to fracture and fragmentation as it occurs in ductile structural components, primarily metals, and on the role of elastomer coatings in suppressing plastic strain localization. The main finding is that the elastomer becomes effective when the bifurcation strain of the ductile metal at which necks begin here's this or to form is roughly comparable to the strain at which the elastomer material shows significant strain rate stiffening.

15. SUBJECT TERMS
high strain rate, plastic strain localization, ductile fragmentation, fracture, elastomer coating, multiple neck formation

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Re: Final Technical Report
Failure of Ductile Materials and Components at High Rate of Loading
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Background and Objectives

In the course of this project, our work has been focused on ductile failure in metals at high rates of deformation. The susceptibility of ductile metals to plastic strain localization, a principal precursor to ductile fracture, is well known. It is a particularly acute problem in metal forming and other industrial operations. Dynamic ductile fragmentation also arises in the metal jet generated upon activation of a shaped charge penetrator. For those situations in which the deformation is slow enough to be regarded as quasi-static, the area has been studied by many researchers. At high rates of deformation, on the other hand, progress has been elusive. This section provides a survey of relevant background materials and identifies the thrust of the research.

At high rates of deformation, plastic strain localization is more pervasive than at slow loading, leading to widespread ductile fragmentation in explosive failures. This is evident in the exploding ring experiment which has been used by a number of investigators to study material behavior at high strain rate. Among the earliest of these is the work of Niordson (Experimental Mechanics 1965) who developed an experimental technique for high rate expansion of ring specimens using electromagnetic loading. In these experiments, after a period of almost homogeneous expansion at a high strain rate, the rings develop multiple necks, some of which provide sites for final fracture. The end result is that the ring breaks up into many fragments. The advantage of this configuration is that it overcomes the complications of wave propagation effects that are prevalent in, for example, the uniaxial tension test, which can cause early localization near the loading end. Several workers have used more or less the same technique to study rapid expansion of rings. Grady and Benson (Experimental Mechanics 1983) performed experiments on copper and aluminum rings and have reported both the fracture strain and the number of fragments/necks as a function of the velocity of expansion, both of which increase with the expansion velocity. More recently, Altynova et al. (Metallurgical Transactions 1996) have performed similar experiments and have reported results similar to those of Grady and Benson (1983). Several key features of ring expansion experiments may be noted: (i) increased fracture strain with expansion velocity, (ii) increased number of necks with increasing expansion velocity, and (iii) minor influence of rate sensitivity on the necking patterns (number of necks). However, understanding of this phenomenon has remained elusive.

Much of the recent theoretical effort in understanding the localization of plastic deformation has been based on Hill's general theory of bifurcation. A summary of this theory has been given by Hill (Muskhelishvili Anniversary Volume 1961). Hill and Hutchinson (Journal of the Mechanics and Physics of Solids 1975) have presented a bifurcation analysis of the quasistatic plane tension test where they computed the bifurcation stresses for various diffuse localization modes (necks). Their study, using a rate independent constitutive relation, indicated that in the quasistatic case the lowest bifurcation stress occurs for the deformation mode with longest wavelength, that is, the pattern of localization is the formation of a single diffuse neck. Hutchinson and Neale (Acta Metallurgica 1977) investigated the effect of strain rate sensitivity (neglecting material inertia) on necking in the uniaxial tension test. They concluded that strain rate sensitivity has a strong influence on the post-bifurcation elongation, and point out the limitations of linearized analysis which fails to predict this effect. In the present context of high strain rate deformation, Fyfe and Rajendran (Journal of the Mechanics and Physics of Solids 1980) have presented a simple analysis along the lines of Hutchinson and Neale (1977) to explain the increased ductility observed in their exploding wire experiments. A theoretical analysis of the influence of material inertia on bifurcations in rapidly expanding sheets has been performed by Fressengeas and Molinari (European Journal of Mechanics A/Solids 1994) using a viscoplastic constitutive relation (no strain-hardening). They conclude that inertial effects slow down the growth of long wavelength diffuse modes while the viscosity effects diminish the rate of growth of the very short wavelength modes. Several numerical models have also been used to study the effect of inertia on localization. Altynova et al. (1996) have constructed a one-dimensional finite element model in conjunction with their ring expansion experiments and reproduced the feature of increasing ductility with the expansion velocity. Their model, however, did not predict the high density of necks as a function of velocity, as found in their experiments. Other numerical studies of ring expansion include that of Han and Tvergaard (European Journal of Mechanics A/Solids 1995) who simulated ring expansion under electromagnetic loading using a dynamic plane strain finite element model with a rate-insensitive plastic constitutive relation. Their computed results, which included the effects of initial imperfections, indicated the formation of a large number of necks.

Against this background, work was undertaken in this project to address several central questions. Among these are the role of various material characteristics (strain rate sensitivity, strain hardening rate and tendency for microvoiding, for example) in dynamic ductile strain localization leading to fragmentation, and the reasons for formation of many closely spaced necks during dynamic ductile fracture. In the later years of the project, it became focused almost entirely on the role of polymer coatings applied to the surfaces of ductile metal components in suppressing strain localization and fracture under explosive loading. The work involved a combined computational and theoretical approach, and it was guided by the experimental evidence available.

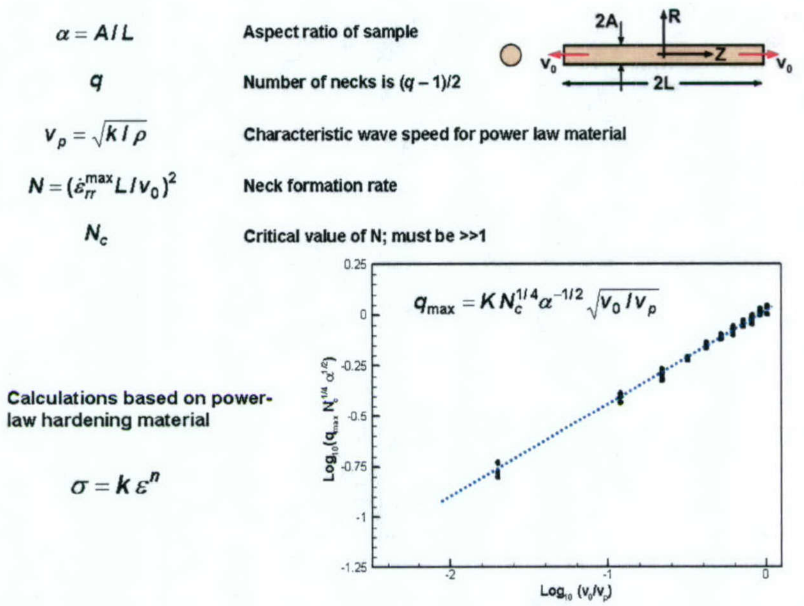

Figure 1: Summary of the dynamic bifurcation calculation based on power hardening plastic response with hardening exponent n and strength parameter k. The frequency of incipient necks along the bar is given by q and the parameter N represents the rate of growth of the neck compared to the mean background strain rate. The model presumed that a critical value of an, say N_c, was necessary to achieve localization. The graph shown in the inset reveals that computed results for virtually all cases considered fell along a straight line, suggesting a particularly simple relationship among the system parameters as being necessary for multiple neck formation.

Technical Approach

The background for the work has been described in detail in the preceding section. The study of ductile failure at high rates of deformation has been addressed through a combined analytical and computational approach. The analytical component has involved primarily studies of bifurcation of plastic deformation fields. In a typical analysis, it is assumed that a component – a bar or plate, for example – made of a strain hardening plastic material is undergoing high rate of deformation that is more or less spatially uniform over the entire component. The deformation is then artificially perturbed in some way to render it slightly nonuniform. The behavior of the perturbation then becomes the focus of study. If the perturbation grows in amplitude at a rate no greater than the rate of background deformation, then the homogeneous deformation is stable and will proceed as a more or less homogeneous deformation. On the other hand, if the amplitude of the perturbation grows at a rate that is large compared to the rate of background deformation, then the homogeneous deformation is unstable. Even though the homogeneous deformation field satisfies all constitutive equations and balance laws, it is energetically less desirable than the nonuniform deformation mode. Consequently, the physical system naturally seeks out the

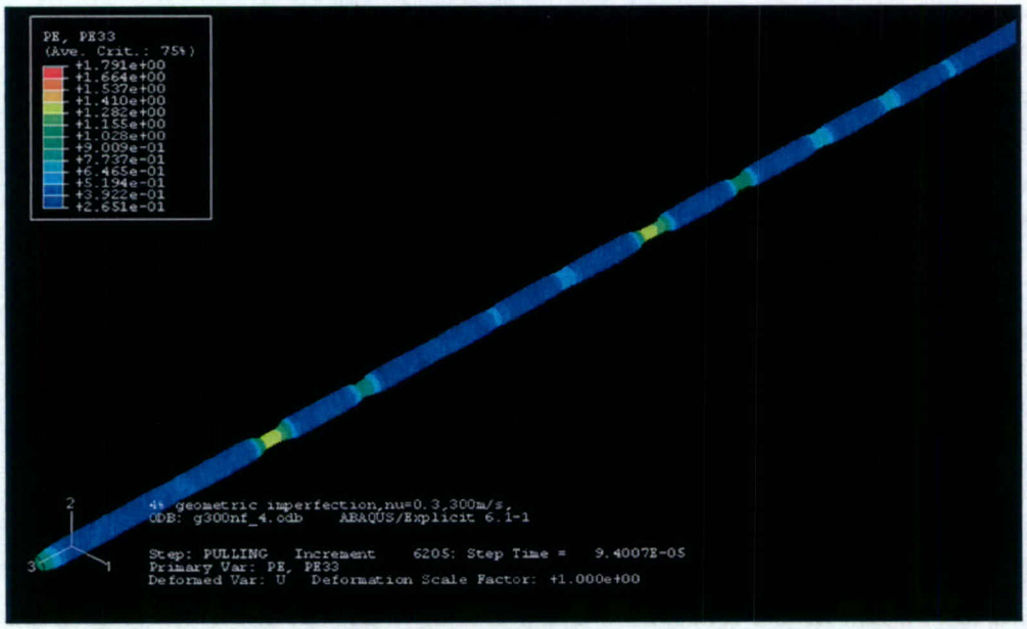

Figure 2: Results of a finite element simulation of high rate extension of a ductile bar at a means strain rate of roughly 104/s. Many incipient necks form along the length of the bar at a mean strain in the range of 30-60plastic strain localization is while others are suppressed. It is the former that eventually lead to ductile fracture of the bar.

nonuniform mode. This is an example of nonuniqueness of solutions, or bifurcation of admissible solutions from the unique branch to multiple branches. The condition for bifurcation can usually be expressed in terms of the rate of loading, geometrical dimensions, and material parameters. An example of bifurcation conditions for a round bar of plastic material, as the nonuniform deformation gives way to a distribution of plastic strain localization sites, or necks, is shown in Figure 1. This work (Shenoy and Freund, Journal of the Mechanics and Physics of Solids, 1999) resolved the long-standing Mott problem concerning ductile fragmentation of brass artillery shells under explosive loading conditions. The perturbation problem is typically linear, so the influence of all perturbations can be examined by assuming sinusoidal perturbation with variable wavelength.

The computational studies of the same physical systems being pursued in parallel with the analytical studies are based on the numerical finite element method, following experience on earlier work (Sorenson and Freund, European Journal of Mechanics A, 1998). The calculations are carried out by means of the Abaqus finite element code (Abaqus Inc., Pawtucket, Rhode Island). Otherwise, the model features are virtually the same as those of the analytical studies. Perturbations in configuration can also be included in the finite element simulations, but nonuniform deformations are not viewed as demonstrating bifurcation behavior if there is a correlation between the imperfection and the nonuniform case in the deformation field. An illustration of a calculation leading to spontaneous formation of a nonuniform deformation in a bar being stretched at high rate is shown in Figure 2.

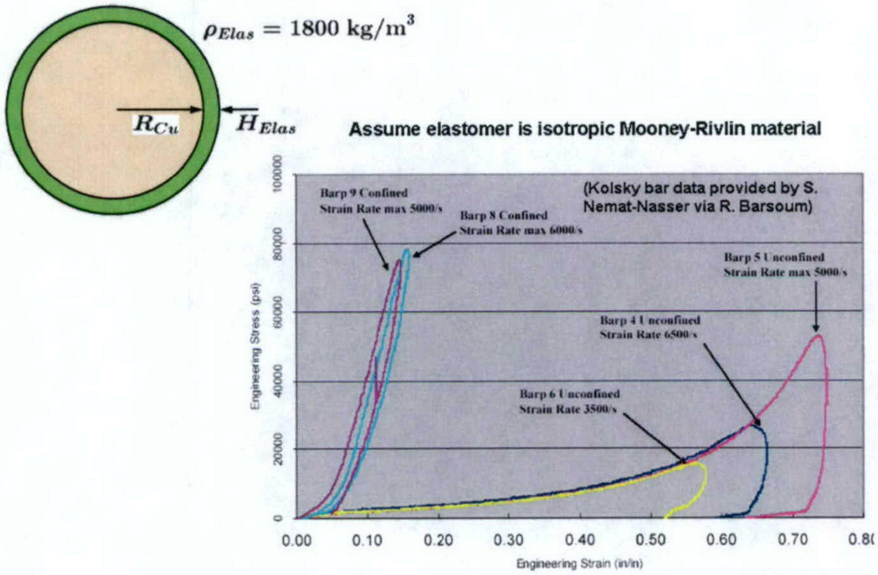

Figure 3:

Summary of Results

Progress was made in the course of this project on the understanding of several issues. Dynamic strain localization phenomena in one dimension, such as occurs in homogeneous tensile bars or in plates undergoing plane strain deformation, are now fairly well understood. However, this class of deformations was re-examined in order to understand the role of an elastomer layer bonded to the surface of the bar in suppressing strain localization. This is a question of significant practical interest because the formation of strain localization sites in ductile materials being deformed at high rates of strain is closely followed by complete ductile fracture. Thus, suppression of strain localization implies suppression of ductile fracture. Furthermore, if the density of localization sites is high, such fracture is the key step in ductile fragmentation.

Because most of our previous work on dynamic necking in ductile bars was based on copper bars, we adopted this body of results as representing a baseline for studying the effects of elastomer layers bonded onto the bar surface. The high strain rate behavior of a particular elastomer of interest to the Navy had been characterized experimentally by Professor Nemat Nasser of UCSD on the basis of Kolsky bar experiments. A diagram showing the radius R_{Cu} of the copper bar and the thickness H_{Elas} of the bonded elastomer layer is shown in Figure 3. Also shown in the same figure are representative elastomer stress-strain curves. For purposes of numerical simulation studies the mechanical behavior depicted in figure was assumed to be the uniaxial behavior of an isotropic Mooney-Rivlin material.

The necking or bifurcation strain of a bar of the copper material at a strain rate of

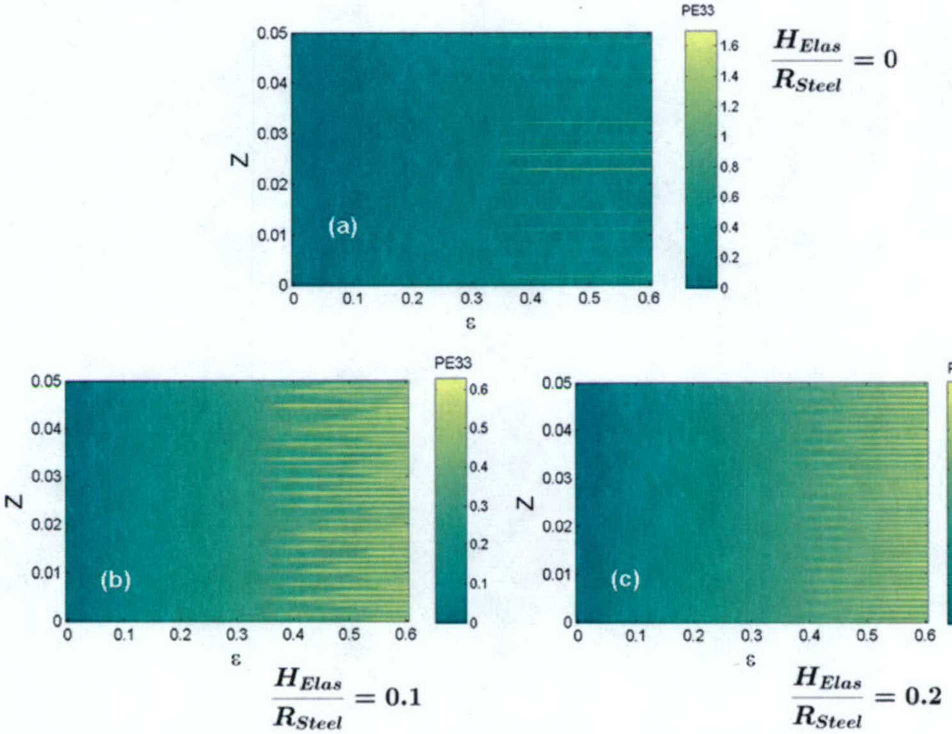

Figure 4: These three figures show contour plots of axial strain along a steel bar being extended at high rate on the plane of axial distance z along the bar and mean extensional strain . The strain distribution is illustrated by color according to the scale on the right. Part (a) is the case of a bar with no elastomer cladding, and it shows regions of highly localized strain approaching 2 separated by regions of very little extensional strain. Parts (b) and (c) show the same deformation process with elastomer cladding on the surface of the bar with thickness equal to 10localization is suppressed and the strain distribution remains more or less uniform up to mean strain of 0.6.

about 8000 per second is roughly 0.3. Through numerical simulation studies, it was established that the role of the added elastomer layer is to suppress the onset of ductile necking, so that this onset occurs at higher strain, similar to the situation for steel as seen in Figure 4. This implies that the composite structure can absorb significantly more energy prior to complete failure than can the copper bar alone.

The degree of suppression of strain localization was found to increase with increasing elastomer thickness up to a thickness of about 10 percent of the radius of the copper bar R_{Cu}. For larger thickness, no further enhancement of resistance was found. These results are summarized in Figure 5. Preliminary results of similar calculations done with bars of DH-36 steel instead of copper showed similar trends; see Figure 4. However, because this steel tends to form necks at lower values of plastic strain than does the copper, the effect is not as pronounced. In general, it seems that the elastomer can be effective only if the structural material itself can deform in

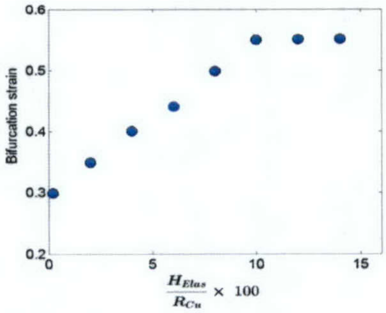

Figure 5: The dependence of the bifurcation strain, the mean axial strain at which localization first becomes apparent, on the thickness H_{Elas} of elastomer coating on the surface of the bar, as a fraction of the radius R_{Steel} of the bar. It is evident in parts (b) and (c) that there is a tendency for strain localization in the presence of elastomer coating at about the same means strain as in a bar without elastomer coating. However, the effect of the elastomer is to suppress the development of fully formed ductile necks from the precursor localization sites.

a ductile manner up to a strain on the order of the strain magnitude at which the stress-strain curve of the elastomer turns sharply upward. This seems to be a key feature in considering the effectiveness of any particular polymer coating.

A preliminary study of a different configuration was also begun, motivated by experimental results reported at the workshop on explosive resistant coatings held at the Natick Center in April of 2004. A series of tests in which a metal projectile was fired at high velocity at a steel plate were described. Results were reported at the workshop for bare target plates and for identical target plates backed by elastomer coatings of different thicknesses and different continuities. We have completed a series of calculations in which continuous layers of elastomer material were added to the plate in successively greater thicknesses. Again, it was found that if the plate could be deformed to fairly large plastic strains under dynamic loading, prior to fracture, then the elastomer was effective in suppressing complete failure.

Pursuing work on structural elements with the potential for biaxial deformation, a bifurcation analysis of a layered ductile structural element undergoing homogeneous, high rate extension has been reported. The basic configuration is illustrated in Figure 6. Formation of multiple strain localization sites provides a precursor to ductile fragmentation, and the objective of the analysis is to investigate the effect of an added surface layer on resistance of the structural element to fragmentation. The analysis shows that, in addition to dissipating plastic work, the outer layer can increase the total energy dissipation prior to fragmentation by increasing bifurcation strain. The analysis also shows that the strain hardening exponent of the outer layer plays an important role in increasing the bifurcation strain; higher values of hardening exponent result in higher bifurcation strain. Strength and density of the outer layer play a secondary role in increasing bifurcation strain. Once a material with a high hardening exponent is chosen for the outer material, its strength plays an important role in increasing the total dissipated energy. The analysis also reveals that, for certain combinations of strength and hardening exponent of the outer layer, the sandwich structure can dissipate more energy than a homogeneous core structure of the same total thickness and length. This is so even when the outer layer is weaker than the core. Energy dissipated per unit mass can be significantly improved by choosing a softer outer layer which displays high strain hardening. Thus, the bifurcation analysis presented here provides a quantitative guideline for material selection in designing layered structures optimized for resistance to fragmentation.

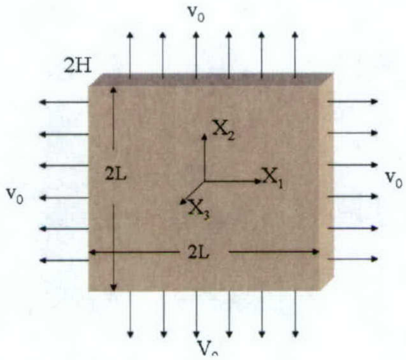

Figure 6: The general configuration used to study bifurcation of deformation in homogeneous and layered plates.

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